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## Thermal/Vacuum vs. Thermal

### Atmospheric Testing of Space Flight Electronic Assemblies

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#### ABSTRACT:

For space flight hardware the thermal vacuum environmental test is the best test of a system's flight worthiness. Substituting an atmospheric pressure thermal test for a thermal/vacuum test can effectively reduce piece part temperatures by 20°C or more, even for low power density designs. Similar reductions in test effectiveness can also result from improper assembly level T/V test boundary conditions. The net result of these changes may reduce the effective test temperatures to the point where there is zero or negative margin over the flight thermal environment.

#### INTRODUCTION

Assembly level thermal testing on hardware intended for space flight is the most perceptive test for uncovering design deficiencies and workmanship flaws. It can also be effective as a reliability demonstration indicator<sup>1</sup>. However, there are many opportunities to compromise the effectiveness of the test starting in the design definition phase of the program. Some compromises can be so bad that the pertinent temperatures during the test are less than what they would be under flight allowable conditions. Compromises which relate to performing thermal testing in an atmospheric pressure environment (T/A) in lieu of thermal testing in a vacuum environment (T/V) for electronic systems intended for space flight will be addressed.

This work focuses on introducing the tools necessary to support a technical

risk evaluation of performing a T/A test in lieu of T/V test. Results of several analyses and tests for the effect of performing a T/A test in lieu of a T/V, are also presented.

#### BACKGROUND

In 1985 a client began the process of reevaluating their technical rational and methodology for choosing between performing thermal testing in a vacuum environment (T/V testing) or in a ambient pressure environment (T/A testing). Their pre 1985 assembly level thermal test rational was to always perform T/V testing unless two conditions were met. These conditions were that the hardware was not sensitive to "pure vacuum" effects AND the watt density of the assembly was low (0.04 watts/cm<sup>2</sup> or less). By mid 1987, it was demonstrated that the old rational was suspect. New rational and methodology were developed to quantify the temperature effects (level/gradients). Research performed on failure physics of space flight electronic assemblies from 1985 to the present has been used in-conjunction with the temperature effect data to evaluate the new approach recommended in 1987.

A survey of industry on assembly level "thermal" testing on space flight electronic hardware, was performed in 1990<sup>2</sup>. One of the questions on the survey was, what are your criteria for subjecting a box to a vacuum environment? The survey found a wide difference of opinion as to when and why the substitution of a T/A test for a T/V test was appropriate. One organization's decision criteria is based on thermal analyses and failure physics factors. Another organization uses a checklist of conditions to be met via analyses before the substitution is allowed. At the other end of the spectrum it was found that only boxes that were known to be sensitive to "pure vacuum" effects (corona, multipactoring etc.) are vacuum tested. Furthermore, this company believed that "digital and

low voltage analog boxes" do not need to be T/V tested at the assembly level. Moreover, the survey found many misconceptions and invalid rule-of-thumbs in use.

The background information necessary to perform an evaluation of the technical risk arising from performing a T/A test in lieu of a T/V test includes:

- (1) An overview of the effects of performing T/A testing in lieu of T/V testing
- (2) The goals of assembly level thermal testing
- (3) A summary of reliability theory, failure physics for electronics assemblies and reliability demonstration theory
- (4) Definition of the appropriate thermal analysis methodology, assumptions and boundary conditions
- (5) Definition of the proper implementation of the T/V test based on the results of the piece part thermal analysis.

A synopsis of these topics along with analyses and test results are presented.

#### Vacuum Effects - An Overview

There are two different physical phenomenon/effects that result from substituting a atmospheric pressure environment for a vacuum environment. They are "pure vacuum" phenomenon and temperature level/gradient effects.

The "pure vacuum" phenomenon include corona and multipactoring. Corona is of concern in the pressure region from about 0.1 to 0.001 torr. Multipactoring can occur starting from the middle of the corona region all the way to near hard-vacuum conditions. These phenomenon are most often associated with RF or high voltage circuits and devices.

The addition of an ambient pressure gas alters key temperature levels and gradients. For a conductively coupled (baseplate to S/C) design the prime thermal path is from the parts to the baseplate via the boards and housing. The addition of a gas into the "simulated" flight environment results in two significant thermal alterations. First, the dominate thermal path from key elements of the assembly (piece parts, solder joints, etc.) are altered because the gas adds a parallel path from these elements to the chamber ambient via the total housing skin. Secondly, artificial parallel paths from the key elements to the flight heat sinking surface are added. These short out any of the high flight thermal resistance paths. The net result of these alterations is the reduction in temperature of key elements at both test temperature extremes. This test temperature reduction is referred to as the  $dT$  effect.

#### ANALYSES & TEST RESULTS

Table 1, presents a summary of analyses and test results supported by the author over the last 5 years to evaluate the  $dT$  effects of performing T/A testing in lieu of T/V testing. Performing T/A testing in lieu of T/V testing reduces the temperature rise from the thermal control surface to key elements (boards, solder joints, parts, etc.) internal to the assembly. Observe that this effect reduces the operating temperatures of the key elements over the whole temperature range i.e. hot testing becomes less severe while cold testing becomes more severe. Reductions in the temperature rises can be on the order of 15°C to 20°C or more. In many cases T/A test reduces temperatures rises by a factor of 2 to 4.

Table 1 also presents power density and hardware type (analog, digital, RF, power supply, etc.) data. Note that neither of these are appropriate "yardsticks" for gauging the sensitivity of a particular design to the effects of

performing T/A testing in lieu of T/V testing. Reference 3 discusses the implications of the packaging design (housing type, board attachment method piece part mounting method, etc.) as they relate to the box level thermal design. It illustrates the synergistic nature of the thermal design parameters on the vacuum flight conditions. This would also be true for a T/A test environment but the additional convection effects must be considered. Therefore, a piece part thermal analysis which includes all parts is required to make a quantitative risk assessment by analyzing both conditions.

#### OBJECTIVES of ASSEMBLY LEVEL THERMAL TESTING

The objectives of an assembly level qualification "thermal environmental test" should be:

##### (1) Design Verification.

Both electrical and mechanical design verification over the expected flight temperature range with margin should be demonstrated. The objective of design verification goal is to verify that the design is not marginal. This is achieved typically by requiring in specification operation in the qualification environment. Moreover, the hardware must still perform in specification after exposure to the non-operating qualification temperature range.

Mil Handbook 1540 qualification test requirements are intended to "verify" the design and workmanship. Moreover, it is intended to be an indication of mission reliability from launch thru "on orbit" spacecraft system checkout. For earth orbiters this process usually requires less than 45 days.

##### (2) A workmanship screen.

Space flight electronic assemblies (black boxes) are becoming more and more complex. For example, complex circa 1970 boxes typically contained on the order of 500 semiconductors. A vintage 1980 box (a Command Data assembly) contained approximately 10,000 semiconductors, 150,000 to 200,000 hand made solder joints and upwards of one hundred million junctions. This trend to more and more complex designs can be expected to continue. As a result workmanship flaws will be impossible to avoid. Mil Handbook 1540 acceptance test requirements are primarily intended to be a workmanship screen.

##### (3) Reliability demonstration.

In an era where customers from congress on down are demanding more cost effective programs, it becomes increasingly important to incorporate a reliability demonstration goal into the environmental test program. In the commercial instrument world where companies are very concerned about warranty costs, prototype testing would be performed to reveal the weakest link. This weak link would be eliminated and testing would continue until the next weakest link was revealed, and so on until the desired level of reliability was demonstrated. The Mil 781 AGREE testing, used in the aircraft industry predominantly as low cycle fatigue life test, is performed on not-to-be-flown hardware. For one-of-a-kind or first-of-a-design protoflight spacecraft, the test to failure approach of the MIL 781 AGREE fatigue testing violates the protoflight concept. Thus a different approach is necessary for this class of spacecraft.

## FAILURE PHYSICS

Reference 1 presents a detailed derivation of the tools required to evaluate the temperature effects of performing T/A testing in lieu of T/V testing. In particular, it presents current reliability theory and derives reliability demonstration models for failure mechanisms found in today's space flight electronic assemblies. A synopsis of these topics will be presented herein to maintain continuity.

### Current Reliability Theory

Old reliability theory<sup>4</sup> (the Bathtub Curve, derived from vacuum tube theory) held that once thru infant mortality, additional testing would not reduce the hazard rate for flight. Current reliability theory (the Roller-Coaster Curve<sup>5,6</sup>) indicates that the longer an environmental test program is, the lower the in flight hazard rate will be, up to wearout. In Figure 1, both theories are illustrated. Individual bumps in the Roller-Coaster Curve can be thought of as being caused by failure mechanisms of a given activation energy. Their order of occurrence is from highest activation energy mechanisms first to lowest last. This weak link elimination continues until wearout.

### Semiconductor Failure Mechanisms

Semiconductors are produced by a series of complex chemical, diffusion and metallurgical processes. The failure mechanisms of these processes are related to imperfections in the manufacturing processes and are most often accelerated by increasing the temperature and/or electrical stress levels (voltage and/or current). The equation which best describes the failure mechanisms for piece parts is a chemical reaction rate equation where, temperature and activation energy are the key parameters. This equation is called the Arrhenius Rate Equation. Figure 2, illustrates the relationship

between reaction rates, temperature level and activation energy. For common piece part failure mechanisms, activation energies range from<sup>7</sup> 0.3 eV to 1.5 eV with 1.0 eV the most frequent<sup>8</sup>. For an activation energy of 0.6 eV, a 10°C increase in temperature (25°C to 35°C) increases the failure rate by a factor of 2.1. For an activation energy of 1.4 eV the reaction rate increases by a factor of 5.7.

Table 2, presents reductions in relative reaction rates associated with various d T effects and activation energy levels. The assumed shearplate (thermal control surface) hot test temperature level is 65°C. The numbers are an indication of the reduction in demonstrated reliability that would result from performing a T/A test in lieu of a T/V test, given the d T effects values shown.

Semiconductors can also have non Arrhenius reaction rate failures. These are most often packaging related and due to low cycle fatigue. However, for most mature device technologies Arrhenius reaction rate type of failures tend to dominate.

Piece Part burn-in tests are designed to screen for Arrhenius types of failure mechanisms. Reference H data for DoD satellite programs found that 30 to 40 percent of the problem/failures reported during assembly level thermal testing (of all types) were due to piece part failures. From this data it is obvious, that burn-in testing does not eliminate all "weak" piece parts. The manufacturing process builds-in workmanship problems AND Arrhenius failures<sup>1</sup>.

### Thermal Fatigue Failure Mechanisms

Thermal fatigue (as a result of thermal cycling) is another failure mechanism which occurs in electronic assemblies. This mechanism is also used to precipitate out many workmanship flaws

(solder joints, PCB shorts/opens, fastener torquing, etc.). Thermal cycling is an accrued damage failure mechanism because failure only surfaces/occurs after exposure to a number of strain cycles. In Figure 3 the log-log relationship between strain and cycles is illustrated. Current solder joint theory indicates that the stiffness of the solder joint/lead system, hot/cold extreme temperatures and the rate of temperature transition affect the rate of strain in solder joints. Moreover, these factors act synergistically<sup>9,10</sup>. For compliant PCB/solder-joint/lead systems, temperatures below room temperature may not strain the joints, assuming that the cold test temperatures are above the glass transition temperature for all materials involved. For stiffer joints, 0°C is currently thought to be the lower limit of the strain range<sup>10</sup>.

Workmanship screens operate on the assumption that a screening strength of  $S$  is required to precipitate the required number of latent failures. A specific screening strength is expressed as  $N$  cycles of magnitude  $y$ , in a given environment (T/V or T/A). For a given temperature range the screening strength varies linearly with  $N$ ; for example, 8 T/V cycles over the range of -24°C to +45°C (shearplate). Performing a T/A test in lieu of a T/V test reduces the upper temperature level obtained. Therefore, to achieve the same test effectiveness would require performing  $X$  times  $N$  cycles. Table 3, presents these "X" factors for various  $d\ T$  effects and upper test temperature levels assuming compliant "joints". Note that for a 45°C shearplate upper test temperature level and a 10°C  $d\ T$  effect, more than twice as many cycles would be required to achieve the same test effectiveness. A 20°C  $d\ T$  effect would require more than four times as many cycles. Thus, a reduction in the hot solder joint temperature can significantly reduce the test effectiveness.

### PROPER TEST SETUP

Choosing the proper test setup is fundamental to performing a thermal test which truly delivers the desired level of demonstrated reliability and/or screening strength. Most often, the assembly level environmental tests are performed by a different group than the one that designed it. Moreover, the thermal implications of the design are not transmitted in a sufficient manner. As a result, comprises often go unrecognized until spacecraft level T/V testing. A brief discussion of the typical T/A environment and the proper T/V test setup for a space flight design which is to be conductively coupled to the S/C thermal control surface, is presented.

### T/A Environment

To maintain a stable environment within an environmental chamber, small temperature differences air-to-box-skin are required. Thus, chamber manufacturers employ large mass flow rates. This in turn translates into high air velocities inside the chambers. Unit's under test are usually placed on a stand inside the chamber. As a result, the "skin" temperature is nearly uniform and about the same temperature as the inlet air. Inside the unit significantly large free convection and gaseous conduction paths exist. Because these paths are added in parallel to the "natural" (conduction and radiation) T/V test environment paths, they short out any "naturally" high thermal resistance paths. High power parts are by necessity almost always well conductively coupled to the housing and therefore they are seldom affected significantly by substituting a T/A environment. However, piece parts that have high thermal resistance case-to-board and board-to-shearplate can be significantly effected. Therefore, the piece part thermal analysis must be performed on all piece parts in both environments.

### T/V Environment

For a unit which was designed to be conductively coupled to the external environment, the unit should be coupled to an isothermal heat sink in the same manner as in flight i.e. same size and number of fasteners, and torqued the same as in flight. If the box level thermal analysis indicated significant gradients in the S/C mounting surface then an isothermal heat sink would not be an adequate representation of the mounting configuration. If the test was performed anyway the result would be lower temperatures and smaller gradients than in reality. Recent test experiences has shown that the effect of not properly simulating the mounting configuration can result in substantially reductions in key temperatures. Where the flight surface can not be presented as isothermal, a prototype of the flight interface (for example a honeycomb panel) should be used such that the baseplate of the unit would have gradients and temperature rises similar to flight conditions. In either case the unit should be blanketed to force all the heat to be conducted to the baseplate of the unit and then conducted across the interface and ultimately into the isothermal heat sink.

Furthermore, the other external surfaces should be blanketing so that all heat is transferred by conduction to the thermal control surface. Not blanketing can significantly compromise the test just as substituting a TA environment for a T/V environment can. For designs which are to be tested in a vacuum environment without a blanket, the external radiant environments must be specified and specifically designed for. The extra costs of specifying and designing for a radiant environment are considerable.

### Other Findings

Flight telemetry sensors are almost always located near these well conductively coupled parts which are the least likely parts to be effected. Thus

using the flight sensors "inside" the unit to evaluate the effect of performing a test in one environment/mounting configuration vs. another is a poor measure of the effect in general.

An environmental test program can be tailored to compensate for the hot level compromise created by performing T/A testing in lieu of T/V testing. This can be done by increasing the number of cycles performed, raising the hot test level or some combination of these. However, this would require extensive thermal mapping testing in a vacuum environment on the first unit or extensive thermal analyses to quantify the temperature effects. Moreover, compromises in temperature gradients can not be compensated for by any practical means.

One clients current rational is to always perform T/V testing. However, if it can be that a unit is not sensitive to pure vacuum effects and the  $\Delta T$  effect for all piece parts is less than  $5^{\circ}\text{C}$  a T/A test may be allowed.

### CONCLUSIONS

A T/V test is clearly a more effective test since it is a flight like environment. The material presented in this paper allows the increase in risk associated with performing a T/A test in lieu of a T/V test to be quantified. The temperature level effects of performing T/A testing in lieu of T/V testing reduces the hot temperature margin, screening strength and test demonstrated reliability. Hot temperature margins can be compromised to the point where there is zero or negative margin between environmental test levels and the flight allowable level (e.g. a test with a planned  $10^{\circ}\text{C}$  margin and a T/A effect  $15^{\circ}\text{C}$  to  $20^{\circ}\text{C}$  would result in negative test margin). Screening strengths can be reduced by a factors of 2 to 4 or more. Test demonstrated reliability can be reduced by factors of 2 to 15 or more.

Decision criteria based on power density or hardware type is suspect. Piece part thermal analyses for both T/A and T/V environments is required. These analyses must include all parts/joints, etc. before a quantitative risk assessment can be made.

Using the Roller-Coaster reliability concept of Figure 1, T/V testing should eliminate more weak links than T/A testing. Therefore, hardware which was T/V tested should have a lower hazard rate in flight than T/A tested hardware.

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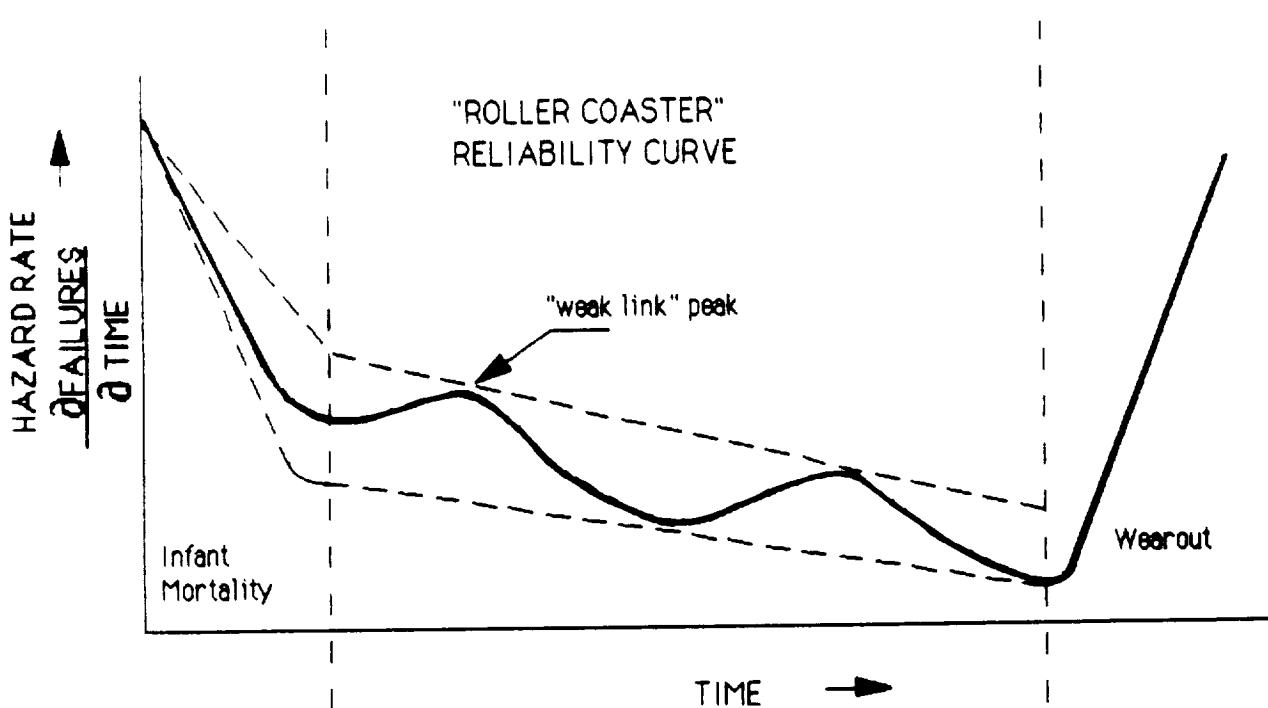
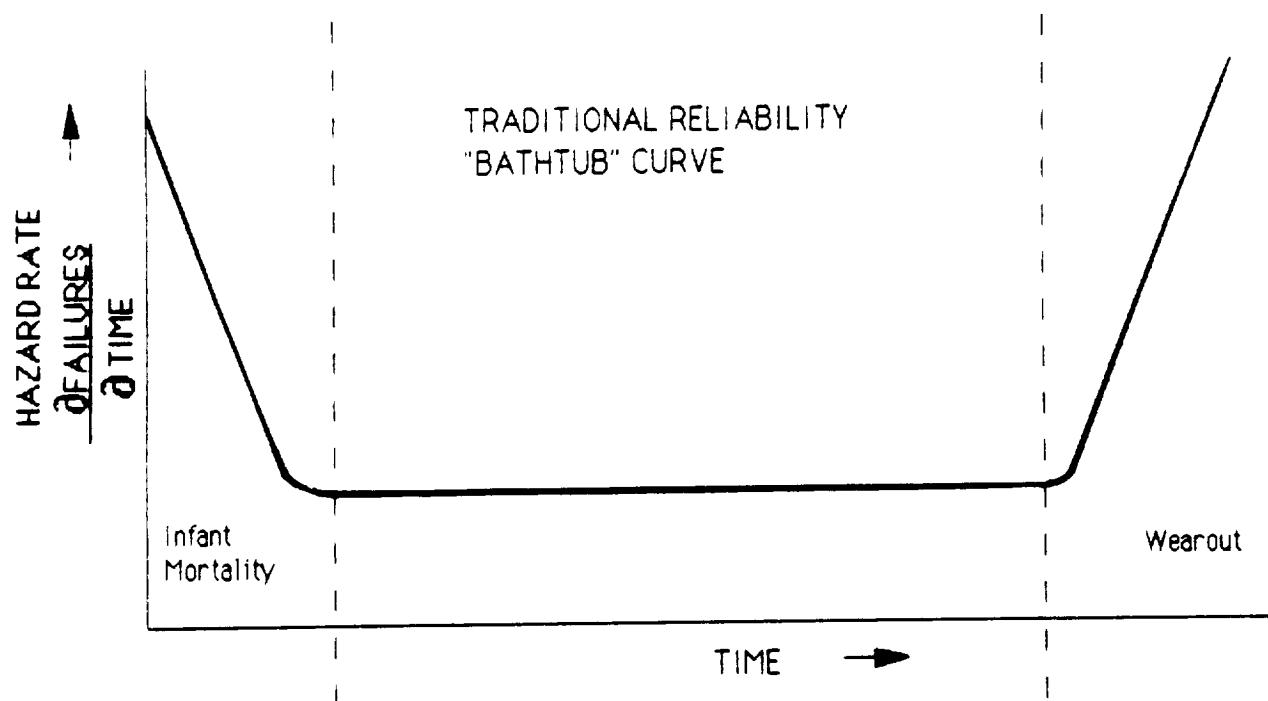


Figure 1. "Roller Coaster" vs. "Bathtub" reliability curves.

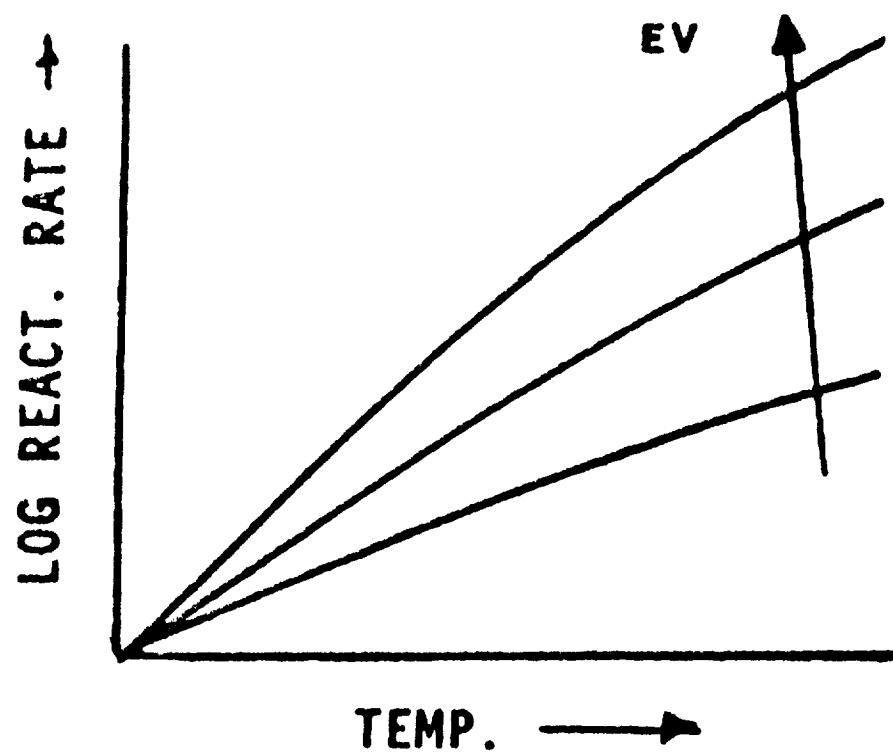


Figure 2. Arrhenius reaction rates vs. temperature and activation energy.

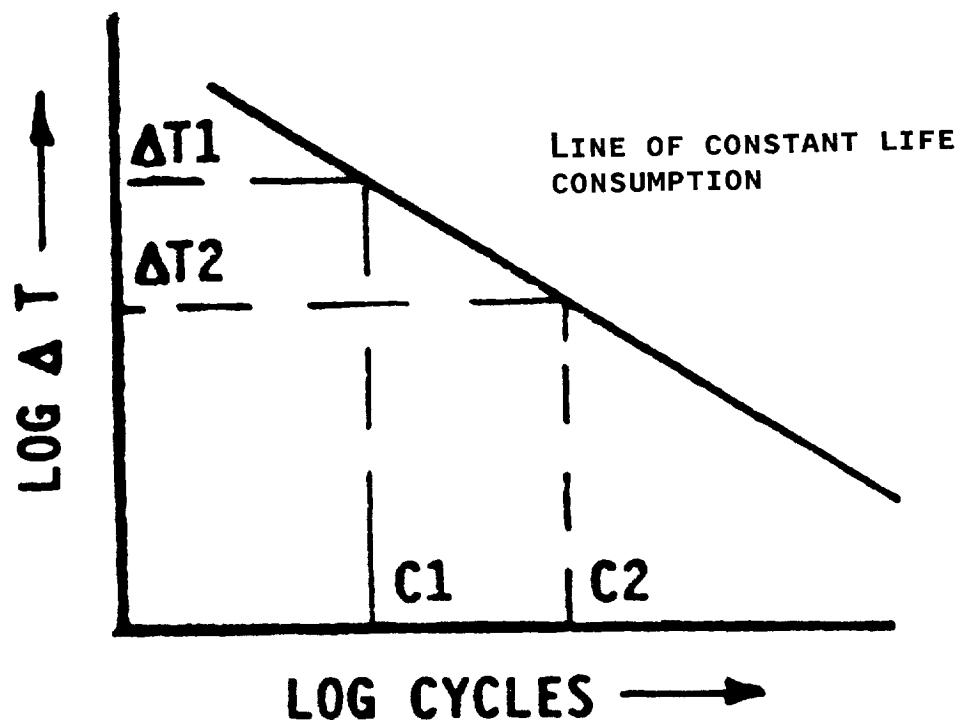


Figure 3. Strain vs. cycles of life for solder joints (strain caused by thermal cycling).

TABLE 1. SUMMARY OF ANALYSES & TEST RESULTS FOR THE  $dT$  effect  
ASSOCIATED WITH PERFORMING T/A TESTING IN LIEU OF T/V TESTING

ASSEMBLY	TYPE	POWER DENSITY W/CM*CM	$dT$ effect		Deg C
			Analysis	Test	
Radar Transmitter	R. F.	0.04	16		(1)
Radar Transmitter	Power Supply	0.04	9		
Radio Reciever	R. F.	0.10	< 9		
Power Distribution	Analog	0.01	< 5		
Data Formater	Digital/analog	0.15	10	10	(2)
Range Dispersion	Digital/analog	0.19	10		
Command Data Bay 3	Digital/analog	0.02	21		
Command Data Bay 4	Ditigal	0.01	16		18
Science Instrument	Digital/analog	0.03	22		20
Output Network	R. F.	0.01	3		

Notes:

- (1) Unit not blanketed during initial T/V test. Estimates for the effect of this indicated that the load on the heat exchanger was approximately twice that dissipated by the unit.
- (2) Test performed for the  $dT$  effect part case-to-housing. Full  $dT$  effect shown is a combination of test and analysis.

TABLE 2. ARRHENIUS REACTION RATE REDUCTION  
FACTORS FOR VARIOUS d T effects &  
ACTIVATION ENERGIES

d T effect	Activation Energy (eV) (*)		
Deg. (C)	.6	1.0	1.4
20	3.1	6.5	14.7
10	1.8	2.6	4.0
5	1.3	1.6	2.0

\* Assuming a 65 C shearplate.

TABLE 3. SCREENING STRENGTH REDUCTION FACTORS ("X" FACTORS) FOR VARIOUS  $\Delta T$  EFFECTS & SHEARPLATE TEMPERATURES

SHEARPLATE TEMPERATURE Deg C	d T effect Degrees C (*)		
	5	10	20
45	1.5	2.2	4.1
55	1.4	1.8	3.0
65	1.3	1.6	2.5
75	1.2	1.5	2.2

\* For compliant solder joints and cold test temperatures above the glass transition temperature for all materials involved.